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Hot electron measurements in ignition relevant hohlraums on the National Ignition Facility

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On the National Ignition Facility (NIF), hot electrons generated in laser heated hohlraums are inferred from the >20 keV bremsstrahlung emission measured with the time integrated FFLEX broadband spectrometer. New high energy (>200 keV) time resolved channels were added to infer the generated >170 keV hot electrons that can cause ignition capsule preheat. First hot electron measurements in near ignition scaled hohlraums heated by 96-192 NIF laser beams are presented.

I. INTRODUCTION

Upcoming experiments on the National Ignition Facility (NIF)[1] will attempt to achieve fusion ignition using mega joule laser-driven hohlraums[2]. The laser beams propagating in the hohlraums generate hot electrons by laser-plasma instabilities[3]. For the current ignition design[4] the hot electrons with energies >170 keV can penetrate through the capsule ablator causing preheat of the deuterium-tritium (DT) fuel[5] resulting in entropy increase that can compromise ignition. On the NIF the ignition hohlraums are heated by 192 laser beams with a shaped pulse as shown in Figure 1a.

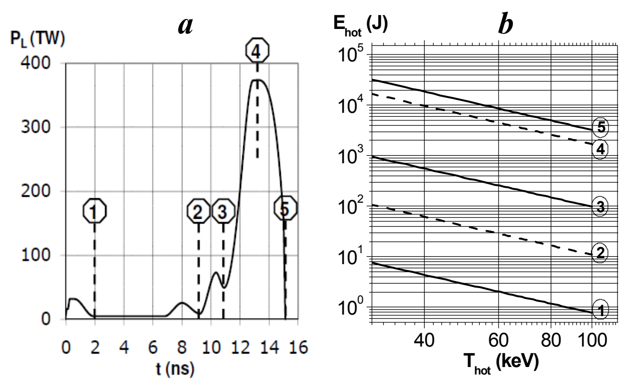

FIG. 1 (a) Laser power for NIF ignition design and (b) hot electron thresholds for ignition as a function of Thot integrated up to different times during the ignition pulse

According to calculations, the acceptable hot electron thresholds that maintain fuel entropy to levels acceptable for ignition are much more stringent at early times than at late times during the ignition pulse[5]. Since only >170 keV electrons can cause capsule preheat, it is easy to show that the total hot electron energy threshold scales with the hot electron temperature as $E_{hot} \sim 1/T_{hot}^2$ over a limited range of Thot (30 – 100 keV) assuming a maxwellian hot electron distribution. Figure 1b shows the calculated thresholds for ignition[6] at different times during the laser drive for an ignition design using a DT filled, Cu doped Be capsule (2.35 mm diameter) placed in a U hohlraum (5.9 mm diameter, 10 mm long)[4], assuming isotropic hot electron generation inside the hohlraums. For T_{hot}=30 keV the allowable fraction of hot electrons out of the total laser energy ranges from 0.02% (E_{hot}=7.6 J) for the first 2 ns to 2.5% (Ehot=30 kJ) at the end of the ignition laser pulse. We infer Thot and Ehot from the hard x-ray bremsstrahlung spectra generated by hot electrons in the hohlraum walls approximated by[3]:

$$I[keV/keV.sr] = \frac{5}{4\pi} \times 10^{11} \cdot \frac{Z}{79} \cdot E_{hot}[J] \cdot e^{-h\nu/kT_{hot}[keV]} \quad (1)$$

On the NIF we measure the absolute >20 keV hard x-ray bremsstrahlung emission from laser heated targets using the Filter-Fluorescer diagnostic (FFLEX).

II. THE FFLEX DIAGNOSTIC

An early version of FFLEX with 8 filter-fluorescer channels in the 20-150 keV spectral range was activated in 2004 during the first hohlraum experiments in the NIF Early Light (NEL) Campaign using the first four NIF beams[7,8,9]. Its detectors consist of NaI(Tl) scintillators coupled to XP2008 photomultiplier tubes (PMT) that are connected to charge sensitive amplifiers (CSA)[8]. Recently FFLEX channels absolute responses were re-measured and a halfraum experiment heated by a single NIF quad gave results consistent with NEL[10].

The 8-channel FFLEX cannot distinguish hard x-rays generated by >170 keV preheat hot electrons, nor can it measure a ~100 keV superhot electron component that would adversely preheat the fuel. Since at >170 keV photon energies no element absorption edges exist, we added two new high energy channels that are high band-pass filter only[11]. With the estimated 15% calibration uncertainties per channel, calculations show that two new channels with typical responses >200 keV and >450 keV are sufficient to resolve two temperature 30+100 keV hot-superhot electron distributions. They also help distinguish between the physics of hot electron generation and since only a few experiments will use truncated laser drives, the new channels are time resolved for maximum data return (<1 ns time resolution). Figure 2 shows the layout of the upgraded FFLEX.

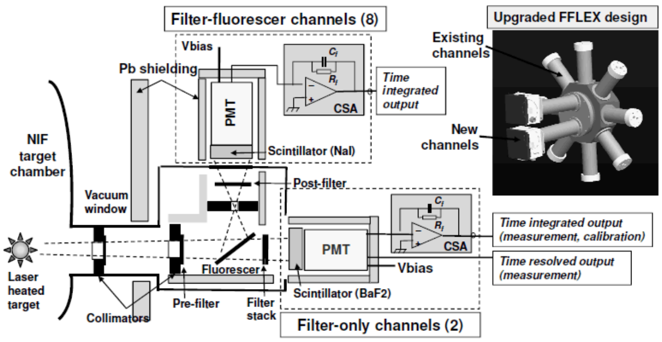

FIG. 2 Layout and design of FFLEX upgraded with the two high energy, filter only channels.

For the new channels fast Hamamatsu R5320 photomultipliers are used, coupled to BaF2 scintillators. The time response of the system that includes 50 m long signal cables measured with a radioactive source in single photon counting mode revealed a 0.7 ns rise time that depends slightly on the PMT voltage. Time resolved and time integrated signals via CSA are acquired by tapping PMT signals off both anode and last dynode. The time integrated outputs are used to measure in situ detector sensitivities using radioactive sources and time integrated hard x-ray spectra, while the time resolved outputs give the history of the hard x-ray signals associated with the hot electrons. Figure 3 shows the spectral responses for the new >200 keV and >350 keV channels, obtained by using filter stacks consisting of Au/Pt/Cu/Al (0.5/0.8/5/3 mm thick) coupled to a 10 mm thick scintillator and Pt/Cu/Al (4/5/3 mm thick) coupled to a 15 mm thick scintillator, respectively. Cu/Al filter combinations are used to suppress the K shell fluorescence of the high-Z filters.

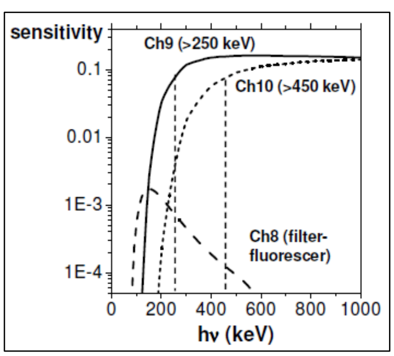

FIG.3 Spectral response of the new high energy channels.

III. HOT ELECTRON MEASUREMENTS IN IGNITION SCALE HOHLRAUMS

Scale 0.7 (3.6 mm diameter x 6.5 mm long) vacuum hohlraums were heated by 96 laser beams with 2 ns square laser pulses with 150-310 kJ total energy to validate measurements of the hohlraum x-ray drive at ignition relevant intensities. At corresponding average laser intensities at the wall of 4, 6 and $8{\cdot}10^{14}$ W/cm^2 we measured 2-T distributions with T_1 in the 3-10 keV range and f_{hot}/T_{hot} of 0.01%/17 keV, 0.02%/20 keV and 0.2%/20 keV respectively. The inferred f_{hot} increase with laser intensity and are consistent with previous hohlraum experiments[8,9,12] in reduced scale (20% in linear dimensions) hohlraums heated by 10-40x less total laser energy as shown in Figure 4. We note that hot electrons fractions start to be significant (~>1%) at ~10^{15} W/cm2.

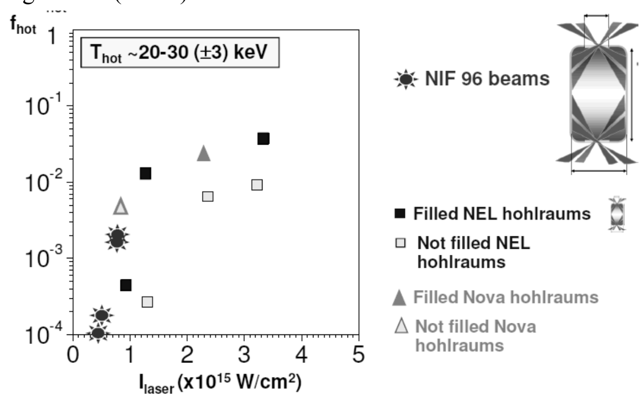

FIG. 4 F_{hot} vs laser intensity measured in NIF multi-beam, NEL and NOVA [8] vacuum hohlraums.

Scale 0.9 (4.6 mm diameter x 8.4 mm long) vacuum and gas filled hohlraums were heated by 192 laser beams and Figure 5 shows a summary of typical measured FFLEX spectra. The new >200 keV Channel 9 gives spectral points consistent with the first 8 channels, showing that there is no high energy cutoff of the hot electron Maxwellian distribution at hν~4kT_{hot}, as suggested by some physics models[3].

Vacuum hohlraums heated by 600 kJ laser energy with 2 ns square laser pulses yielded two-temperature spectra with T_1~10 keV and f_{hot}=0.2% at T_{hot}=30 keV. At similar $8{\cdot}10^{14}$ W/cm2 laser intensity, this result is consistent with that measured in the scale 0.7 NIF hohlraums (Fig. 4).

Gas filled hohlraums at room (CH4) and cryogenic (He-H mix, pure He) temperatures with symmetry capsules surrogates were heated with ignition-like laser pulses (Fig. 1) with pulse lengths of 11 ns and ~500 kJ total laser energy. For a laser intensity of $5{\cdot}10^{14}$ W/cm2, i.e. lower than in vacuum hohlraums (Fig 5), the measured FFLEX spectra are also fitted by 2-T distributions with T1~10 keV and Thot~30 keV, but with 10x less spectral flux, yielding considerably lower fhot=0.02% as expected from the scaling with laser intensity (Fig. 4).

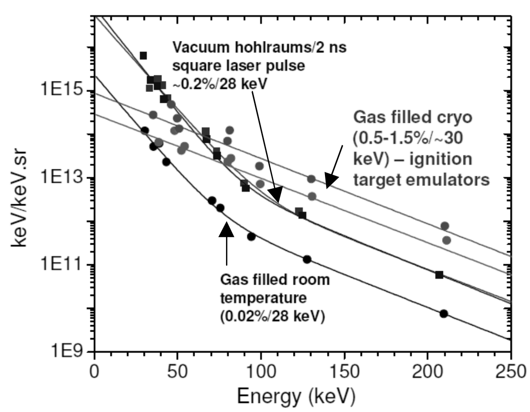

FIG. 5 FFLEX spectra in vacuum hohlraums and in room temperature and cryogenic gas filled hohlraums (scale 0.9/500 kJ laser energy).

At similar laser intensities and pulse shapes, cryogenic gas filled (He-H mix, pure He) ignition hohlraum emulators containing gas filled capsule surrogates yielded considerably higher f_{hot} in the 0.5-1.5% range at T_{hot}~30 keV, attributed to increased SRS on the inner beams. Specifically, the wavelength shift between inner and outer beams was increased to generate outer to inner beam laser power transfer[13]. For similar total energy deposited in the hohlraums, f_{hot} increases with total inner beam power at the wall consistent with the increasingly prolate shape of the symmetry capsule cores[14]. Laser backscattering measurements show that SRS is dominated by the ~15% total scattered energy from the inner beams compared to ~1% scattering from the outer beams.

Hard x-ray signals measured by high energy channels 9 and 10 were used to determine the history of hot electron generation. Figure 6 shows the total laser power measured in scale 0.9 hohlraums and the hot electron power P_{hot} inferred from Channel 9 signals normalized to E_{hot} as inferred from the analysis performed with Channels 1-9 (Fig 5). In all hohlraums the hot electron signals peak during the high power part of the laser drive. For cryogenic gas filled hohlraums with ignition-like shaped laser pulses hard x-ray hot electron signals peak at 11 ns and are generated only at late times during the main laser power. and thus the measured f_{hot} < 1% can be compared to the late time ignition thresholds of 2.5% (Fig. 1b).

Channel 9 measures the x-rays generated by the >170 keV capsule preheat electrons. For f_{hot}=1.1% and T_{hot}=30 keV we infer 250 J of preheat electrons which is 2x lower than the requirement scaled to the lower total laser energy compared to the ignition design that will be driven by 1.2 MJ.

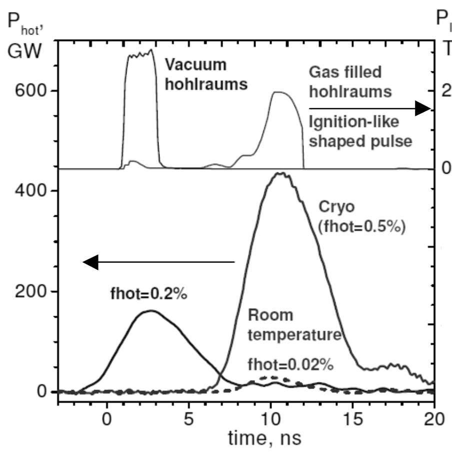

Figure 6 Total laser power, and Phot inferred from Ch. 9 hard x-ray signals and Ehot inferred from time integrated

Our measurement did not show any early time hot electron generation that are expected during the laser beam burnthrough the LEH windows. The dynamic range of 100 of the PMT signals is, however, 10x to low than required to measure the early time ignition hot electron thresholds (Fig. 1b). Therefore more measurements with truncated laser pulses and increased FFLEX sensitivity are required to measure early time hot electrons in ignition type cryogenic gas filled hohlraums. Systematic hot electron measurements were performed in scale 0.9-1.07 cryogenic gas filled hohlraums driven by ignition-like shaped laser pulses with 11-19 ns duration and 0.5-1.0 MJ laser energy. The results and data trends will be discussed elsewhere.

IV. ACKNOWLEDGMENT

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V. REFERENCES

[1]G.H. Miller, E.I. Moses and C.R. Wuest, Nucl. Fusion 44, 228 (2004).

[2]J.D. Lindl, P. Amendt, R.L. Berger, S.G. Glendinning, S.H. Glenzer, S.W. Haan, R.L. Kauffman, O.L. Landen, Phys. Plasmas 11, 339 (2004).

[3]W. Kruer, Physics of Laser Plasma Interactions, Addison-Wesley Publishing Co. (1988).

[4]S.W. Haan, D.A. Callahan, M.J. Edwards, B.A. Hammel, D.D. Ho, O.S. Jones, J.D. Lindl, B.J. MacGowan, M.M. Marinak, D.H. Munro, S.M. Pollaine, J.D. Samolson, B.K. Spears, L.J. Suter, Fusion Sci. Technol. 55, 227 (2009).

[5]D. Meeker, N. Meezan, L.J. Suter, S. Haan, Bull. Am. Phys. Soc. (CO1.002) (2004).

[6]S.W. Haan, LLNL, private communication 2008.

[7]C.L. Wang, Rev. Sci. Instrum. 52, 1317 (1981).

[8]J.W. McDonald et. al., Phys. Plasmas 13, 1 (2006).

[9]E.L. Dewald, O.L. Landen, L.J. Suter et al, Phys. of Plasmas 13, 1, (2006).

[10]E.L. Dewald, L.J. Suter, C. Thomas, S. Hunter, D. Meeker, N. Meezan, S.H. Glenzer, E. Bond, J. Kline, S. Dixit, R.L. Kauffman, J. Kilkenny, O.L. Landen, Proceedings IFSA 2009.

[11]C. Stoeckl et al Rev. Sci. Instrum. 72, 1197 (2001).

[12]M.D. Cable, H.N. Kornblum, R.L. Kauffmann, LLNL Internal Annual Report (1985).

[13] P. Michel, L. Divol, E. A. Williams, C. A. Thomas, D. A. Callahan, S. Weber, S. W. Haan, J. D. Salmonson, N. B. Meezan, O. L. Landen, S. Dixit, D. E. Hinkel, M. J. Edwards, B. J. MacGowan, J. D. Lindl, S. H. Glenzer, and L. J. Suter, Phys Plasmas 16, 042702 (2009).

[14]S. H. Glenzer, B. J. MacGowan, P. Michel, N. B. Meezan, L. J. Suter, S. N. Dixit, J. L. Kline, G. A. Kyrala, D. A. Callahan, E. L. Dewald, L. Divol, E. Dzenitis, M. J. Edwards, A. V. Hamza, C. A. Haynam, D. E. Hinkel, D. H. Kalantar, J. D. Kilkenny, O. L. Landen, J. D. Lindl, S. LePape, J. D. Moody, A. Nikroo, T. Parham, M. B. Schneider, R. P. J. Town, P. Wegner, K. Widmann, P. Whitman, B. K. F. Young, B. Van Wonterghem, J. E. Atherton, E. I. Moses, Science 327 (2010) 1228.